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## **Numerical simulation of the thermal and mechanical behavior of cold-formed steel composite floor under fire conditions**

Jixian Peng<sup>1</sup>, Wei Chen<sup>\*2</sup>, Jihong Ye<sup>3</sup>, Zhengliu Wang<sup>4</sup>

### **Abstract**

Cold-formed steel (CFS) building structures are generally acknowledged as green and industrialized buildings, and the fire resistance behavior has become an important issue. Previous studies were mainly to investigate the fire performance of load-bearing CFS walls lined with different panels. Based on the finite element (FE) software package, ABAQUS, this paper presented a numerical simulation on a new CFS channel joist – ALC (autoclaved lightweight concrete) composite floor under fire conditions. Finally, the present numerical simulation of CFS composite floor in fire was compared with previous full-scaled fire experiments of such floors. The results showed that the temperature progression of the CFS floor section was well predicted with acceptable accuracy. The time-dependent vertical deflection of the CFS floor was well described and the fire resistance time of CFS floor system was well predicted with an underestimation of less than 6% and an overestimation of less than 10%.

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**Key words:** ABAQUS; numerical simulation; CFS composite floor

### **Introduction**

In recent years, a growing number of mid-rise cold-formed steel (CFS) structures have been constructed and utilized as residential and commercial buildings. At the same time, the understanding of the fire performance of such structures has generated increasing concerns in fire safety design [1]. For the CFS structures, previous fire experimental and theoretical studies were mainly focused on the fire performance of CFS wall systems [1-8]. As the only horizontal separating element, the CFS floor system also plays an important role in the fire safety of CFS buildings. However, very limited research has been carried out on the thermal and mechanical behavior of CFS floor systems under fire conditions [7-10]. Among these investigations, a new CFS channel joist – ALC (autoclaved lightweight concrete) composite floor was developed by our research group, with the intent of simultaneously improving the fire performance and construction efficiency of such floor for potential applications in mid-rise CFS structures. Five full-scale CFS composite floor assemblies were examined under fire and uniformly distributed loading conditions. The impact of various parameters, including the presence of cavity insulation, load ratios and the type of boards was discussed.

In this paper, the thermal response of newly developed CFS composite floor is simulated by a two-dimensional heat transfer model. The mechanical behavior of such CFS composite floor in fire was simulated by a three-dimensional structural model. The main purpose of present investigation is to provide reasonably prediction for the fire performance of CFS floor assemblies.

### **Heat transfer model**

The finite element (FE) software package, ABAQUS, was used to check the suitability of performing numerical simulation of CFS floor assemblies in fire. The thermal response of CFS floor was simulated by a two dimensional heat transfer

model which represented the cross section of such floor, as shown in Fig. 1. All the component members of CFS Floor were modeled by using the four node linear quadrilateral element (DC2D4). The mesh size of ALC boards and concrete topping was  $25\text{mm} \times 25\text{mm}$  and  $25\text{mm} \times 15\text{mm}$ , respectively. A smaller mesh size of ceiling boards and steel joist was adopted which were about  $5\text{mm} \times 1\text{mm}$  and  $5\text{mm} \times 1.5\text{mm}$ , respectively. Line contact was set at the interface of adjacent ceiling boards, the base layer ceiling boards and bottom flange of steel joists, the top flange of steel joists and ALC boards as well as the ALC boards and concrete topping. The corresponding thermal contact resistance at the interface of adjacent ceiling boards was not included. The initial temperature of the heat transfer model was set as  $20^\circ\text{C}$ . The environment temperature on the fire and ambient side of heat transfer model was specified by the standard ISO 834 time-temperature curve and  $20^\circ\text{C}$ , respectively. The emissivity was taken as 0.8. The convection coefficients on the fire side and ambient side surface of heat transfer model were taken as 25 and  $10 \text{ W}/(\text{m}^2\text{C})$ . The cavity radiation on the floor cavity was considered based on the assumption of greybody radiation and isothermal and iso-emissive cavity facets [11]. The effect of heat convection on the floor cavity was not included.

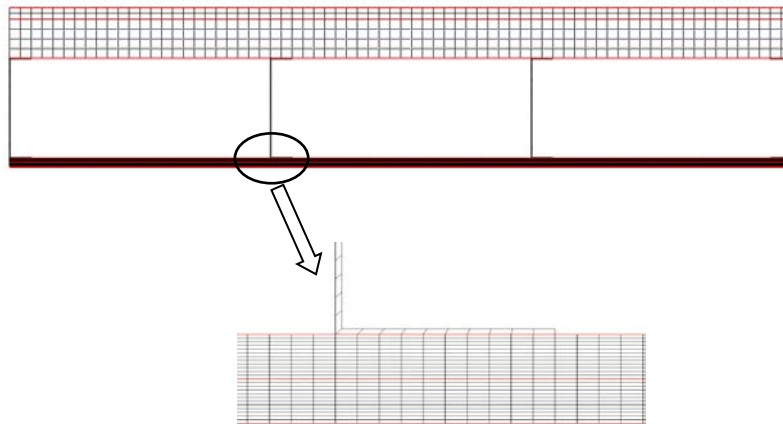


Fig. 1 FE model for the temperature response of CFS composite floor

Varied thermal physical properties, including density, specific heat and thermal conductivity of the component materials of such floor at elevated temperatures were adopted in the present modeling. The thermal physical properties of cold-formed steel are taken from EC3 Part 1.2. The thermo-physical properties of fire resistant gypsum plasterboard, bolivian magnesium boards and ALC boards were obtained from authors' previous experiments [12]. For the rock wool, Eq.(1) for thermal conductivity [13] and 800 J/(kg°C) for specific heat and 120kg/m<sup>3</sup> for density were used in the present modeling. For the concrete topping, the corresponding thermo-physical property at room temperature were used as input data, which was 1050 J/(kg°C) for specific heat and 0.93W/(m°C) for thermal conductivity and 1900kg/m<sup>3</sup> for density. In addition, based on the present fire experiments of CFS floor assemblies, it was assumed that the fall off of 12mm fire resistance gypsum plasterboard, 12mm bolivian magnesium board, 15mm bolivian magnesium board and rock wool insulation occurred when the ambient side of such materials achieved 650°C, 600°C, 550°C and 550°C, respectively.

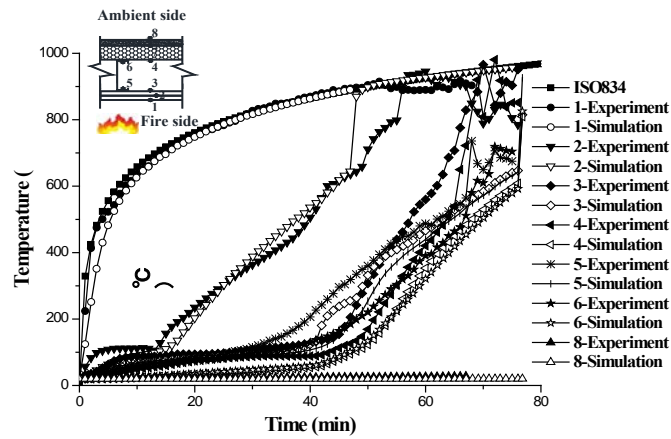
$$\begin{aligned} k_{rock} &= 0.036 + 0.000116T & 0^\circ\text{C} < T \leq 100^\circ\text{C} \\ k_{rock} &= 0.0419 + 3.28 \times 10^{-5}T + 2.63 \times 10^{-7}T^2 & T > 1200^\circ\text{C} \end{aligned} \quad (1)$$

where  $k_{rock}$  represented the thermal conductivity of rock wool insulation.

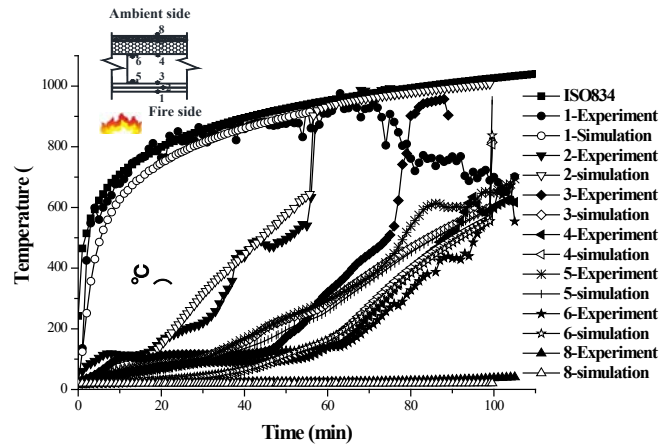
The heat transfer model was calculated by Full-Newton method. First, an initial heat transfer step (Step 1) was built. When the average temperature at the interface of double layers of ceiling boards reached to the critical temperature (for instance, 650°C for fire resistant gypsum plasterboard), the collapse of face layer ceiling board was assumed to have occurred and the initial step was stopped. In Step 2, all the elements on the face layer ceiling boards were killed and the environment temperature and heat convection were subjected to the fire side of base layer ceiling boards. The remaining model continued to be calculated until the collapse of base layer ceiling boards happened. The next steps took similar process until the presetting time was achieved.

Fig. 2 showed time-temperature profiles obtained from the present heat transfer

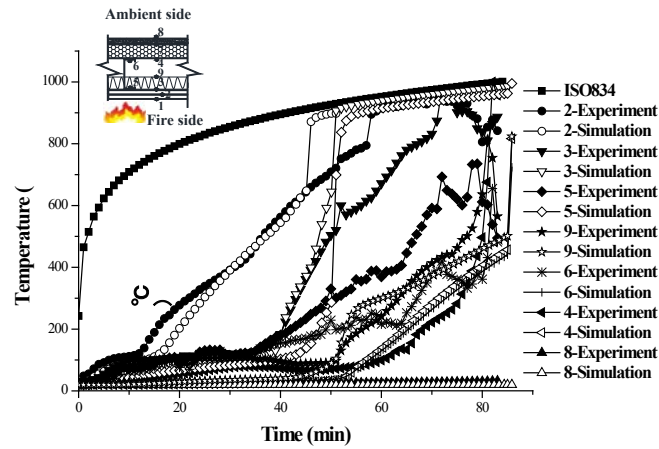
model and fire experiments. The average experimental results of specimens F1 and F3 [14] were used in Fig. 2(a), due to their similar configuration. It can be seen from Fig. 2 that the FE results of temperature responses were close to the fire experimental results with acceptable accuracy. The collapse of ceiling finish was well simulated in the FE modeling, implied by a sudden rise temperature of the ambient side of ceiling boards which was merged with the temperature of the fire side.



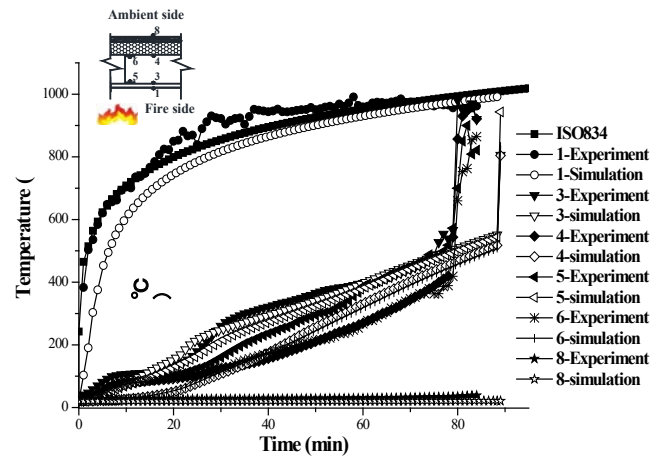
(a) Average of F1 and F3



(b) F2



(c) F4



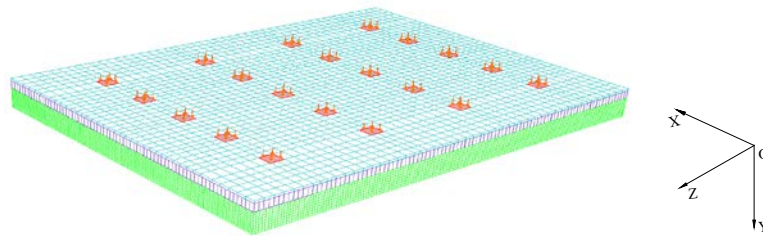
(d) F5

Fig. 2 Comparison of time-temperature profiles obtained from heat transfer model and own experiments

### Structural model

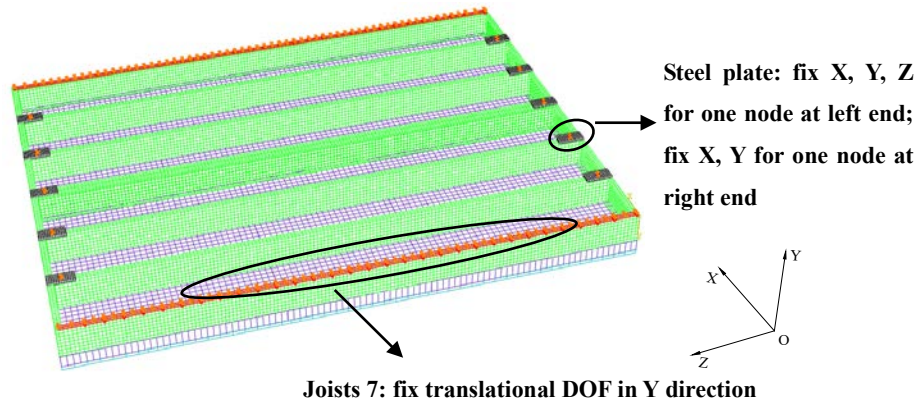
The mechanical behavior of CFS floor in fire was simulated by the present three

dimensional structural model, as shown in Fig. 3. The CFS frame was modeled by linear quadrilateral element (S4R) with mesh size of about  $30\text{mm} \times 30\text{mm}$ . Each ALC board was simplified as rectangular solid with dimension of  $1800 \times 600 \times 100\text{ mm}$ , neglecting the concave-convex profile along the long edges of such boards. Both the ALC boards and concrete topping was modeled by 8-node reduced integration linear brick element (C3D8R) with mesh size about  $50\text{mm} \times 50\text{mm} \times 100\text{mm}$  and  $100\text{mm} \times 100\text{mm} \times 30\text{mm}$ , respectively. The ceiling finish of CFS floor was not included in the present structural model, due to the collapse of such material at the final stage of fire exposure. Ten steel plates ( $200\text{mm} \times 100\text{mm} \times 20\text{mm}$ ) were built by C3D8R element with mesh size of  $20\text{mm} \times 20\text{mm} \times 10\text{mm}$  and located under the bottom flange of joist supports to reduce the effect of stress concentration at joist ends. The screw connectors of CFS floor assemblies were simplified by coupling the translational DOF (degree of freedom) of connected nodes in X, Y and Z directions. Surface to surface contact was set at the interface of adjacent ALC board joints as well as the interface of the web of double C-shape joists. Tie constraints were adopted at the interface of ALC boards and concrete topping as well as the interface of steel plate and bottom flange of joist end. The translational DOF of the center node of each steel plate was fixed in X, Y and Z directions at the left supports of floor. For the right supports of floor, the translational DOF of the center node of each steel plate were fixed in X and Y directions. In addition, the translational DOF in Y direction of bottom flange of joists 1 and 7 (Fig. 3(b)) were fixed because they were laid on top of the steel ring beams of the furnace.



(a) Side view of structural model





(b) Back view of structural model

Fig. 3 FE model for the thermal mechanical response of CF floor

The ideal elastic-plastic model was used to represent strain-stress constitutive relation of cold-formed steel at room and elevated temperatures. The average elastic modulus of cold-formed steel material obtained from the present steel joists was tested as 203GPa and the corresponding 0.2% proof stress (yield strength) was 385MPa at room temperature. The thermal expansion coefficient and degenerate material properties of Q345 cold-formed steel at elevated temperatures were obtained from authors' previous transient state experiments [15]. The linear elastic assumption was taken for the ALC boards, concrete topping and steel plate with the elastic modulus of 1800MPa, 24GPa and 206GPa, respectively. According to the present fire experimental situation, the vertical loads were applied on the ambient side of structural model as shown in Fig. 3(a). Steel joists 2~6 adopted the simulated temperature results of points "5" and "6" in Fig. 2 as the temperature inputs, except for the left and right supports of steel joists 2~6. In addition, the cross section of steel joists 2~6 assumed to take the following temperature distribution, as shown in Fig.4. The temperature gradient along the longitude direction of steel joist was not considered in the present structural model. Besides, the ALC boards, concrete topping and the other parts of steel frame used the ambient temperature (20°C) throughout the modeling.

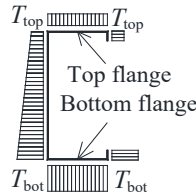


Fig. 4 Temperature distribution of the cross section of CFS joists 2~6

In the thermal mechanical modeling, the eigenvalue buckling analysis was firstly carried out, and the first mode of structural model which was about the local buckling of steel joist was used for the definition of initial imperfection. The maximum value of initial imperfection was set as 1.5mm [16]. After that, a nonlinear analysis was executed by using the full newton method until the structural failure was achieved. The predicted failure mode of the structural model was shown in Fig. 5 and similar to the experimental results [14]. Fig. 6 showed the vertical deflection at the mid-span of five floor assemblies and the predicted fire resistance time obtained from the structural model. In general, the simulated time dependent vertical deflection of floor assemblies compared well with the experimental results. The predicted deflection increased faster than those from experimental results at the final stage of fire exposure. In addition, the accuracy of the predicted fire resistance time was also acceptable with the absolute relative error of less than 10%. Therefore, the present finite element modeling could provide reasonably prediction for the fire performance of CFS floor assemblies. But, time consuming problem cannot be neglected and at least 6 hours were took for the present heat transfer and thermal mechanical modeling of every CFS floor assembly in fire (Intel Xeon CPU E3 3.3GHz and 8.0 GB memory).

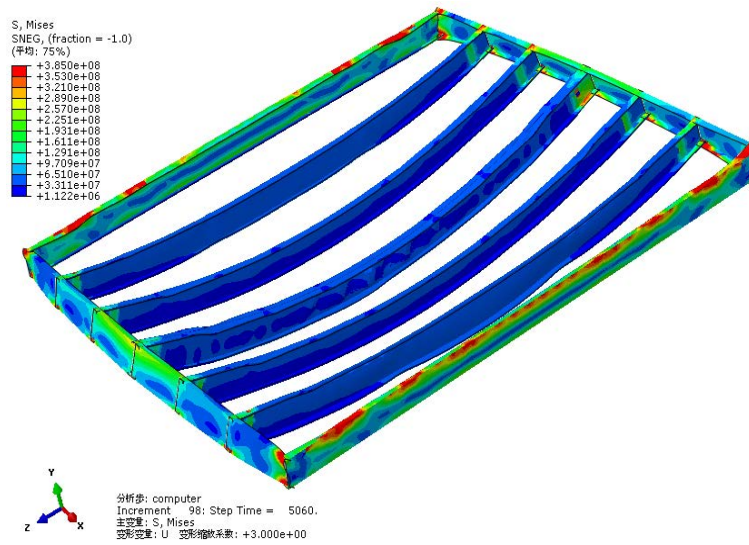
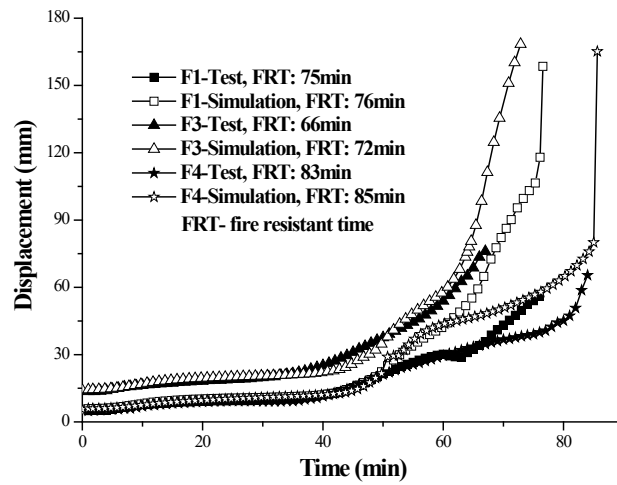
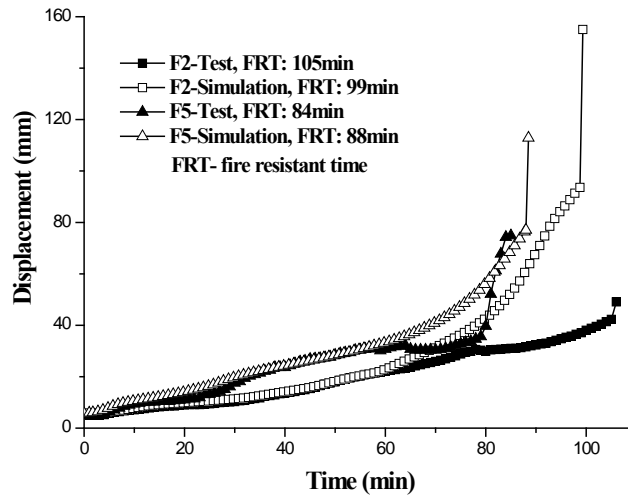


Fig. 5 Failure mode of the structural model at elevated temperatures



(a) Assemblies F1, F3 and F4



(b) Assemblies F2 and F5

Fig. 6 Comparison of time dependent vertical deflection between experimental and predicted results at the mid-span of five assemblies

### Conclusions

This paper developed a new CFS composite floor that has the advantages of quick construction and acoustic isolation. The effect of load ratios and configuration of the ceiling finish were taken into account and the following conclusions were drawn from this work: Both the heat transfer model and structural model were built by using the FEM software package, ABAQUS and the simulation results were close to the experimental results with acceptable accuracy. Hence, the FEM software could be used for the fire performance prediction of CFS composite floor.

### Acknowledgments

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